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Properties of a Formal Method for Modeling Emergence in Swarm-Based Systems

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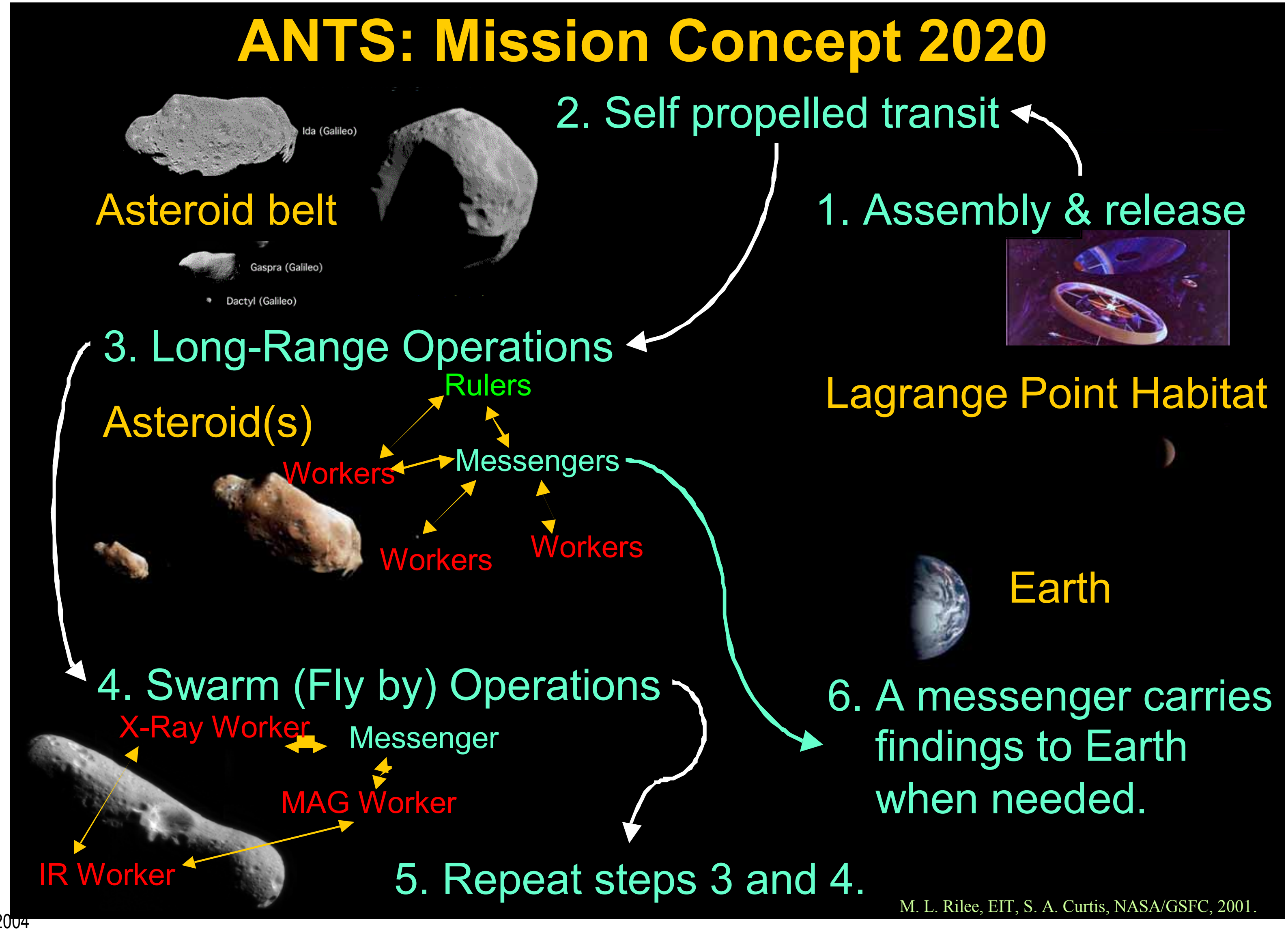
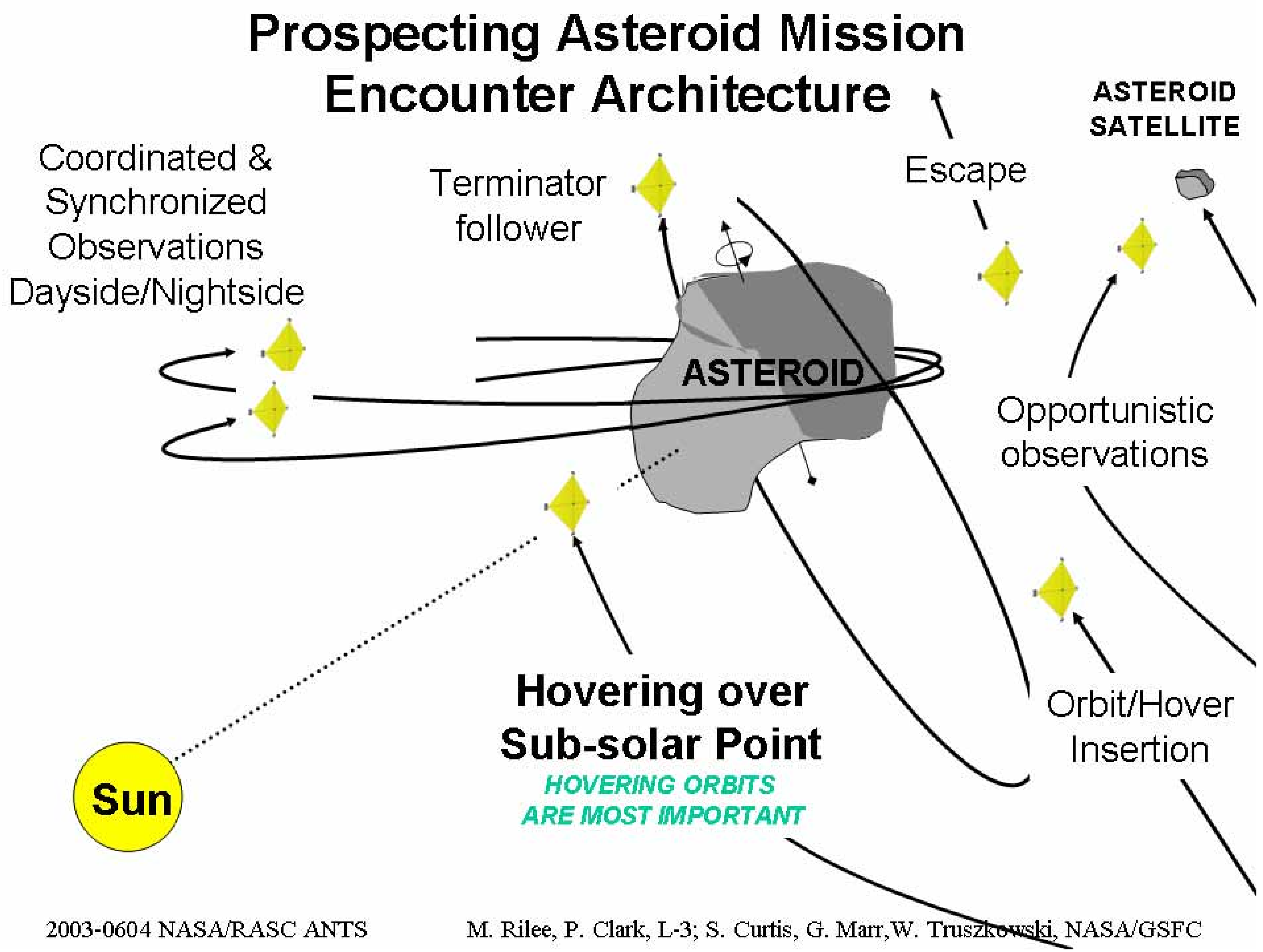
Motivation

- Future space missions will require cooperation between multiple satellites/rovers
- Developers are proposing intelligent, autonomous swarms to do new science
- Swarm-based systems are highly parallel and nondeterministic
- Testing these systems using current techniques will be difficult to impossible

ANTS Mission



ANTS MISSION



2003-0604 NASA/RASC ANTS M. Rilee, P. Clark, L-3; S. Curtis, G. Marr, W. Truszkowski, NASA/GSFC

Difficulty of Testing Swarms

- Emergent properties
- Highly distributed and parallel
- Large number of interacting entities
- Worse than exponential growth in interactions
- Intelligent entities (capabilities increase over time)
- Total or near total autonomy
- There is very little experience in verification and validation of swarm-based systems

Why formal methods?

- Have been developed over the past 30 years
- Have a mathematical basis which allows proof of correctness
- Are excellent for finding errors in concurrent systems
- Could significantly increase assurance for operations

Approach

- Survey formal approaches used on agent-based, multi-agent and swarm-based systems
- Identify parts of the ANTS mission to specify as an example
- Apply most promising approaches from the survey to the ANTS mission
- Evaluate methods based on time to perform specification, errors or omissions found, length of specification, ability to do automated checking

Formal Methods Survey

- **Criteria for Surveying Formal Methods**
  - Emphasis given to formal methods used for:
    - Swarm, multi-agent, or distributed specifications
  - Evaluated based on:
    - Concurrency support, algorithm support, tool support, formal basis, used in agent-based specifications, used in swarm-based specifications

Formal Methods Surveyed

- **Process Algebras**
  - CSP, CCS, Pi-Calculus, I/O Automata
- **Model-Oriented Approaches**
  - Z, B, FSMs, Statecharts, Petri Nets, X-Machines
- **Logics**
  - Temporal, Real Time, BDI, KARO
- **Other Approaches**
  - Artificial Physics, Mathematical Analysis, Game Theory, UML, Hybrid Approaches, Approaches used for Swarms

Formal Methods Survey Results (partial)

Name	Concurrency Support	Algorithm Support	Tool Support	Formal Basis	Used in Agent-Based Specs.	Used in Swarm-Based Specs.
Artificial Physics	Yes	Yes	Yes	Yes- (Mathematical)	Yes	Yes (limited)
B	No	Yes	Yes	Yes (Set Theory/ Pred. Logic)	Yes	No
BDI Logic	Yes	No	Yes	Yes (Logic)	Yes	No
CCS	Yes	No	Yes	Yes (Algebraic)	Yes	Yes (WSCCS)
CSP	Yes	No	Yes	Yes (Algebraic)	Yes	No

Formal Methods Survey Results (partial)

Name	Concurrency Support	Algorithmic Support	Tool Support	Formal Basis	Emergent Behavior Anal.	Used in Swarm-Based Specs.
Cellular Automaton	Yes	Yes	Yes	Yes (FSM)	No	Yes
Com. X-Machines	Yes	Yes	No	Yes (Formal Lang.)	No	Yes
Unity Logic	Yes	No	Yes (limited)	Yes (Logic)	No	Yes
WSCCS	Yes	No	Some (Prob. Workbench)	Yes (Process Alg.)	Yes (Markov Chain)	Yes

Formal Methods and Swarms

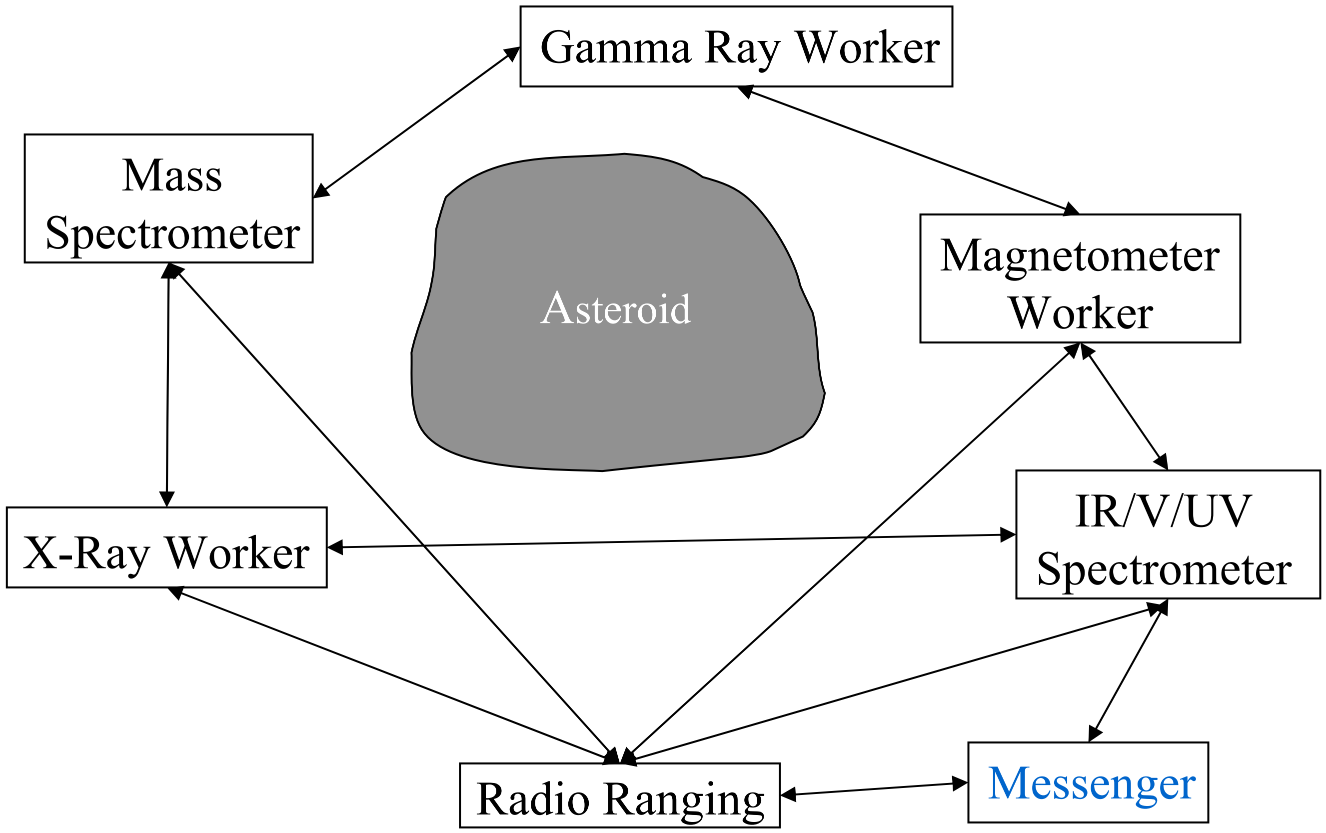
- **Formal methods used for swarms**
  - ◆Weighted Synchronous Calculus of Communicating Systems (WSCCS)
  - ◆Communicating Stream X-Machines
  - ◆Unity Logic
  - ◆Dynamic Emergent System Modeling Language (DESML)
  - ◆Cellular Automata

ANTS Specification

- **Virtual Experiment**
  - Team leaders communicate goals to workers
  - Workers make measurements of asteroids
  - Communicate results back to team leaders
  - Team leaders send other workers to asteroid
  - Models are made for other workers to use (e.g. size, spin rate, etc.)
  - Workers coordinate/cooperate to take measurements
  - Results are sent back to leaders for goal updates

ANTS Virtual Experiment

Self Directed Exploration



ANTS Specification

- **Attributes of Virtual Experiment**
  - Collaboration and Cooperation
  - Distributed/Parallel Processes
  - Algorithmic for single spacecraft

Specifications

- CSP
- WSCCS
- Unity logic
- X-Machines

Evaluation of Formal Methods

- **CSP**
  - Strengths
    - Specifying inter-process protocols
    - Identifying race conditions
    - Easily translated into model checking language
  - Weaknesses
    - No mechanism for analyzing emergent behavior

Evaluation of Formal Methods

- **WSCCS**
  - Strengths
    - Process algebra strengths
    - Specifies priorities and probabilities of actions
    - Rules for predicting behavior
  - Weaknesses
    - Ability to track and model goals and other aspects of the spacecraft

Evaluation of Formal Methods

- **Unity Logic**
  - Strengths
    - Strengths of logic-based systems
    - A method for reasoning about predicates and the states they imply
    - A method for defining specific mathematical and statistical calculations to be performed
  - Weaknesses
    - Not rich enough for reasoning about emergent behavior

Evaluation of Formal Methods

- **X-Machines**
  - Strengths
    - State-based system with memory
    - Executable
  - Weaknesses
    - No robust means for reasoning about or predicting behaviors beyond standard propositional logic

Conclusion

- Blending of methods seems to be the best approach for specifying swarm-based systems
- Blending of priority and probability aspects of WSCCS with memory and transition function aspects of X-Machines is a possibility and will be further researched

Summary

- Researching formal methods for swarm-based systems and future missions
- Swarms are highly parallel and distributed systems with emergent behavior, which are difficult to verify
- Have identified formal methods used for swarms and possibly other appropriate methods
- Have specified parts of the ANTS mission with candidate methods
- Evaluated methods for specifying and analyzing emergent behavior of swarm-based systems